A Quantitative Assessment of the Climate Benefits and Economic Costs of a Smaller World Population[*]

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Abstract: Human activity generates carbon emissions. This fact has led many to conclude that declining fertility will improve living standards for future generations, through reductions in long-run temperatures. We show that this is incorrect—not because the harms of global warming will not be severe—but because this reasoning ignores key results from economics and demography. First, *population momentum* ensures that even immediate changes in fertility rates have only small impacts on the total population size in the near-term, while emissions intensities of economic activity remain highest. Further, there are well-studied costs of population decline: small populations generate less of the innovation that propels economic growth and a retiree-heavy age structure stresses existing economic resources. Modifying a leading climate-economy model to account for these forces, we show that a large and stable world population robustly implies higher average living standards than a small and shrinking population, accounting for climate impacts.

Keywords: Population decline; endogenous economic growth; climate change.

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Introduction

A smaller global human population would reduce carbon emissions. This fact informs an important view in climate policy and science, which holds that reductions in population growth should be a key component of the efforts to mitigate climate harms (1; 2; 3). Though it is widely accepted that a smaller population would raise the average living standards of future generations by mitigating climate change, this account is incomplete. It neglects two core features of economic growth and population: First, a depopulating planet has fewer of the innovators that are crucial in driving the economic growth that has improved human wellbeing (incomes, health, longevity, education, etc.) historically (4; 5). Second, a shrinking population is an aging population, with a worse dependency ratio (i.e., fewer workers per retiree). This strains social support and lowers living standards overall (6; 7). Given these countervailing considerations, it is an open and critical question whether a smaller or larger future population would result in higher living standards for future generations.

Here we establish that a larger future population results in gains to average living standards via economic growth that exceed the well-known and severe climate costs of human activity, measured on a common scale of GDP-per-capita value. For climate costs, this accounting includes not only lost economic productivity, but also mortality effects, sea level rise, and other non-market harms. A key mechanism behind our surprising, yet robust, conclusion is *population momentum*: Changes to fertility rates affect population size too late to meaningfully impact long-run temperatures. Even if it were possible to instantly raise or lower fertility rates today, doing so would significantly affect population size only slowly, with a many decades-long lag, after decarbonization is projected to be advanced under even pessimistic scenarios. This implies both that population policy is quantitatively insufficient as a climate mitigation response and that the gains associated with a larger future population—via the better "dependency ratio" or productivity growth—need not be large to dominate the tiny difference in temperature generated by the larger future population. We show that the gains from either mechanism individually exceed the losses from climate damage.

Adding Demographics and Endogenous Growth to an Integrated Climate Assessment

We characterize the costs of a larger population using the same models and parameters that have been used to calculate the social cost of carbon and inform environmental policy regarding the value of future damages from greenhouse gas emissions. Because our aim is to quantitatively assess the common claim that climate mitigation is a rationale for population reduction (1), we focus on climate harms (though in the Supplementary Materials we include a sensitivity analysis showing that our results are robust to incorporating the consequences of increased particulate air pollution). Specifically, we begin with DICE (8), the most widely used climate-economy model. DICE—because of its transparent and parsimonious structure—is a useful focus, though we confirm that our results are not contingent on any DICE-specific assumptions. We then innovate by incorporating two facts of population growth that are now well established in macroeconomic research but are unaddressed by the integrated assessment models used in prior climate evaluations.

First, we add "endogenous economic growth," by which economic resources contribute to the innovation that propels economic growth and improves living standards. A world of more people generates more of the *non-rival* ideas and innovations that everyone benefits from. These advances in knowledge spring from richer populations (semiconductors), poorer populations (oral rehydration therapy), and cross-population partnerships (high-yield seeds and the agricultural Green Revolution). Unlike rival goods—a fish that is eaten by one person cannot be eaten by another—ideas are not diminished in availability as more people use them. Once germ theory (or calculus or TCP/IP or mRNA gene editing) is developed, it can be applied endlessly without additional resource use. Therefore, the per-capita stock of knowledge is the total stock of knowledge; it grows with population and so benefits from scale. Paul Romer's Nobel prize-winning work formalized this concept (9); its logic underpins leading theories of long-run endogenous economic growth (4; 5; 10; 11); and the modern macroeconomic consensus, supported by historical evidence, is that population size contributes to long-run economic growth via this mechanism (11; 12). Our first contribution is to embed standard representations of this fact—calibrated to external empirical estimates of knowledge production (12; 13)—into DICE, allowing us to quantitatively study the trade-off between the additional emissions and the additional ideas, innovation, and knowledge produced by a larger population. (Endogenous growth effects enter as total factor productivity (TFP); see Methods.)

Second, we add a representation of the macroeconomic consequences of the age structure of the population. In a depopulating economy, because each generation is smaller than the last, there are more retirees per worker than in a stable population. If this "dependency ratio" is large, the goods and services generated by the few workers must be shared among many. This fact of population age structure—though mundane, mechanical, and entirely predictable given fertility and mortality rates—is important for social wellbeing via its economic consequences. It is already a cause of serious concern for the governments of low-fertility populations. DICE, like many simplified economic models, ignores that some consumers are too young or too old to also be workers. We add this feature to DICE, separately tallying population and productive workers according to the age structure contained in the population projections we compare.

Constructing Alternative Population Paths

Within this framework, we contrast living standards—defined in the usual way in integrated climate assessments as average GDP per capita, with non-market goods converted to GDP-equivalent value—under two paths for future population. These population path inputs are detailed in Methods and plotted in Fig. 1. The first path, *Depopulation*, is adapted from the United Nations (UN) World Population Prospects 2019 Medium projection (14) and represents demographers' central, consensus projection of the demographic future (14; 15; 16; 17): Fertility rates worldwide will converge to below-replacement levels and global population growth will become permanently negative in the early 22nd century. The second path, *Stabilization*, represents a possibility in which low-fertility societies (instantly) transition to replacement fertility today, so that there is no long-run decline in population size.

The two population paths are compared under "current policy" (18) and "low ambition" climate policy scenarios, where the latter corresponds to temperature changes aligning with the IPCC's worst-case RCP8.5 scenario (19). We ask whether—for either fixed set of assumptions about emissions mitigation in these scenarios—larger populations are worse for human living standards on net, as determined in an integrated climate assessment. We also evaluate an alternative comparison between *Depopulation* and a population path that uses and extends the UN 2019 "High" fertility variant in the Supplementary Materials.

Results: Warming, Damages, and Net Living Standard Impacts

Our main result—plotted in the bottom panels of Fig. 2—is that a larger population yields higher average living standards for future generations, net of climate harms. These panels show the ratio of living standards (measured as average GDP per capita value, including non-market gains and losses as mentioned above) under *Stabilization* relative to *Depopulation*. Within one to two hundred years, the net benefits of *Stabilization* become large—a 9.7% relative increase in living standards by 2150 and 26.7% by 2200 under current policy (Fig. 2e).

To understand the core result, consider first the top panels of Fig. 2, which depict the emissions and climate impacts of population stabilization. The left panel uses a current policy trajectory (18); the right uses the low climate ambition trajectory. For either level of policy ambition, global temperatures are only slightly increased under *Stabilization* relative to *Depopulation*: 4.26° versus 4.20° in 2200 under current policy; 6.38° versus 6.04° in the low ambition scenario.

Figs. 1 and 2 imply that a difference of about 4 billion people by 2200 (*Depopulation* versus *Stabilization*) yields only a tiny temperature reduction benefit. How? This particular result about the relatively small impacts of population on temperature, anticipated (without our quantitative integrated assessment of costs and benefits) by Bradshaw and Brook (20) and Budolfson and Spears (21), reflects facts of timing. The first fact, from demography, is population momentum: Population *size* (a stock) is slow-changing over the span of a few decades, even if fertility *rates* (flows) change fast. In post-demographic-transition populations, the new, larger cohorts make up a very small fraction of the total population at first. So the size of the population is only 9.5% larger under *Stabilization* in 2100 despite that it is 59.4% larger by 2200. The second fact arises from technological and policy progress: Emission reduction efforts—underway in many countries today—are projected to continue to advance in the coming decades. Total emissions are declining by 2050 in the current policy scenario and a little after 2100 under the low ambition scenario (Fig. 2a,b). Of course, even the current policy scenario is low-ambition relative to shared international climate goals (such as 1.5 degrees of warming). Fig. 2a,b shows that our results do not rely on assuming unrealistically fast rates of decarbonization; in even these high-warming scenarios, most of the population size increase occurs at a time of significantly less emissions per person than today.

Because of this timing, the climate costs of a larger population are very small, and even modest benefits of population arising from endogenous innovation or dependency ratio effects can dominate the harms. Fig. 2 illustrates this by isolating these forces (panels c,d) and weighing each separately against the full climate damages (panels e,f): Via endogenous innovation, a larger population leads to total factor productivity that is 2.7% larger under *Stabilization* a century from now. This gap increases to 11.5% by 2200. The dependency ratio has non-monotonic effects. Initially, the additional children worsen the dependency ratio, a finding anticipated by Marois, Gietel-Basten, and Lutz (22). Once these children become workers, it improves. *Stabilization* eventually reaches a dependency ratio in which 7 percentage points (13.2%) more of the population are workers, relative to *Depopulation* (Fig. 1). If the two economic mechanisms are combined, they positively interact: A more productive dependency ratio enables a larger fraction of a larger population to work towards non-rival innovations.

For completeness, we also compare long-run living standards under *Depopulation* to a population path which uses and extends the UN 2019 "High" fertility variant, in which aggregated fertility rates are higher than in the *Stabilization* path but lower than in the twentieth century. This alternative comparison (Fig. S4) differs in that it generates more contrast in dependency ratios and innovation effects and that the High variant generates greater climate damages. But the comparison yields the same qualitative insights as our main exercise: the net effect of the larger population is to raise average living standards.

Extensions and Robustness: Alternate Climate and Economic Models

It is important to understand that we are identifying the implications that follow from combining consensus demographic projections and facts with standard components of integrated assessment models and macroeconomic growth models. Therefore, we inherit the well-studied advantages and limitations of these components. To gauge sensitivity to these, in Fig. 3 we present the results of 240 robustness checks, each from a different set of modifications to the baseline model. These modifications and their consequences are detailed in Supplementary Materials A. Included are alternative models in which background climate mitigation policy is assumed to be much more or much less ambitious than current policy; models where the climate dynamics are governed by FAIR (23), which is an alternative geophysical model recommended by the National Academies (24) (see Fig. S2 for a replication of Fig. 2 with FAIR); models in which the impacts of population size on economic growth are assumed to be much smaller (25); models in which climate damages are assumed to be much larger than in DICE (26); models that include the economic consequences of tipping points in the climate system (27); models in which damages impact the growth rate rather than the level of economic output (28) or reduce total factor productivity itself (29); models in which idea production is fueled by aggregate economic activity, rather than population (9); and, for conservatism, models in which the emissions elasticity of population is larger than DICE assumes (30).

Scenarios in Fig. 3 span from ambitious futures in which temperature change meets 2° targets and global living standards grow nearly five-fold by 2100 to scenarios with temperature change as extreme as the IPCC's worst-case RCP8.5 scenario and in which living standards *fall* this century (see distribution panel within Fig. 3). In all cases the *additional* warming caused by larger populations remains small: Policy choices leading to terrible climate damages continue to do so regardless of population size, and policy choices successful in constraining temperatures are not meaningfully bolstered by a smaller population. Other extensions of the model include better incorporating the importance of human capital (31; 32; 33) by amending the dependency ratio to instead use the "productivity-weighted labor force dependency" ratio of Marois, Gietel-Basten, and Lutz (22). (See Supplementary Materials B for a full discussion.) Across all scenarios and model variants, the large net benefits of *Stabilization* relative to *Depopulation* remain (median net gain by 2150 in living standards across scenarios in Fig. 3 = 9.4%; mean = 8.8%).

A limitation of our analysis is that DICE is a global integrated assessment model, which prevents examining geographic heterogeneity in any outcome. Our purpose here is to establish the global facts, including that population momentum (a demographic force that holds in all regional populations) implies that population size changes are slow and predictable relative to the urgency of emissions reduction. Like the other modeling variants examined in Fig. 3, substituting a regional model would not alter these core results. Future work interested in geographic disparities in the population age structure, productivity growth, and climate impacts could investigate these issues in a regional model.

Additionally, a larger population would have environmental impacts beyond climate change, including for biodiversity, non-human animals, and non-carbon air and water pollution. Our main analysis does not address these, though Fig. S5 shows that our conclusions are unchanged by accounting for the air pollution impacts of population size. Other environmental considerations are nonetheless important avenues for future research. Here, we focus on comparing the benefits for human wellbeing of a larger population to the costs of climate change, because it receives prominence in scientific and policy conversations as the key environmental challenge of our time.

Discussion

Global depopulation is projected to begin within the lifetimes of people alive today (Fig. 1a). Once population growth becomes negative, no currently foreseen demographic force would reverse the path. Survey evidence from many low-fertility populations reports that, if less constrained, many women would prefer to have more children, roughly at replacement-fertility levels (34; 35; 36; 37). Our findings suggest that, if investments in human development, gender equality, labor markets, support for children and care work, and assisted reproductive technology could support women's ability to achieve this preference, such investments would have net positive spillover effects via the dependency ratio and innovation, overwhelming the harm of very small increases in long-run temperatures (although we conjecture that such investments must be substantially more ambitious than familiar policies) (37; 38).

We conclude by noting that, while our substantive findings are at odds with advocacy calling for depopulation as a partial solution to the climate emergency, our findings are consistent with the measured historical changes in human wellbeing. Over the last century, both population size and the costs borne by humans due to climate change have risen dramatically, but there has nonetheless been an increase in average living standards globally (e.g., incomes, food security, health, and education; see Fig. S6) that is more rapid than in any other time in history (4; 11; 39).

Methods

Our method is to input two exogenous population paths, which we construct from published UN projections, into a version of the DICE 2016 climate-economy model (40) that includes a standard representation of economic innovation and growth (10). We also disaggregate the total population into children, workers, and retirees according to the age structure in the population paths at each point in time. We do not optimize climate policy (optimization is done in many implementations of DICE); we instead choose a fixed path of mitigation rates. All data, code, and replication materials are available at `https://github.com/kevinkuruc/SemiEndogenous_DICE`.

Modifications to DICE 2016

Fundamentally, DICE combines three features: (a) a neoclassical model of economic growth where labor, (accumulated) capital, and economic efficiency determine production, (b) a reduced-form representation of greenhouse gas emissions, concentrations, and temperature consequences, and (c) a damage function that translates temperature changes to future losses of economic well-being. Formally, gross output, Y^G, is determined by Equation 1. Per capita consumption c is equivalent to per capita income less savings and determined by Equation 2. Climate damages D are represented as losses to GDP, but are calibrated to include the monetary value of non-market harms (e.g., health and mortality effects). Annual damages are a non-linear function of temperature T (above pre-industrial) as in Equation 3.

$$Y_t^G = A_t K_t^{\gamma} L_t^{1-\gamma} \tag{1}$$

$$c_t = \frac{(1 - D_t) Y_t^G - I_t}{N_t} \tag{2}$$

$$D_t = \theta_1 T_t + \theta_2 T_t^2 \tag{3}$$

In (1), A is the measure of productive efficiency that we endogenize, K is the stock of economic capital, and L is the labor force. In (2), D is the fraction of production lost to climate damages, I is global savings/investment, and N is the global population. The subscript t denotes the period. The DICE baseline damage function in (3) is simple with only scalars θ_1, θ_2 determining the magnitude of this quadratic function—we explore multiple alternative specifications in our robustness exercises (see Supplementary Materials A).

The version of DICE we modify is publicly available on William Nordhaus' website (`https://williamnordhaus.com/dicerice-models`) and has been translated to other software and coding languages that we build from (see `https://www.mimiframework.org/`). As the baseline model has been explained in detail elsewhere (8), we limit our discussion to the subcomponents relevant to our modifications. We make two major (and one minor) modifications to the model for our baseline results.

First, we modify the process by which total factor productivity (TFP, A) advances. In DICE, TFP is a representation of productive efficiency, dictating how much output is produced from a fixed set of inputs (see Eqn 1). In Nordhaus's DICE, growth in A is exogenous.

In contrast, drawing on insights from the literature on modern economic growth, we allow for resources—namely, people—to contribute to economic growth (11). Specifically, the production of new ideas determines TFP growth according to the form of Equation 4, following the semi-endogenous growth literature (10):

$$g_{A,t} = \frac{\Delta A_t}{A_t} = \alpha_t L_t^{\lambda} A_t^{-\beta}. \tag{4}$$

Here, $g_{A,t}$ is the growth rate of A in year t; α_t is a scaling factor between the labor force and the production of ideas, determined by the share of the labor force participating in idea production as well as the productivity of this sector; λ allows for intra-period diminishing returns to research effort; $\beta > 0$ allows for the possibility that there are dynamic diminishing returns to knowledge accumulation.

Note that the functional form in Equation 4 does not assume that TFP growth is exponential. It is β that governs the trajectory of TFP over time. Consider that for a fixed α, L: $\beta = 0$ implies that growth rates are constant (and hence A grows exponentially); $\beta = 1$ implies that growth is linear, which has been argued better matches historical TFP growth (25). Likewise, λ and β determine how much additional knowledge is produced for a scaling of population. Eden and Kuruc (41) show that a 1% increase in population leads to a $\frac{\lambda}{\beta}$% increase in long-run knowledge accumulation in a model that uses the same semi-endogenous structure.

Drawing from industry and aggregate evidence documented in Bloom et al. (13), we set $\lambda = 1, \beta = 3.1$.[1] Regional evidence in (12) finds similar quantitative magnitudes for the response of living standards to population. Note that this implies growth is slower than exponential for a fixed α, L, despite population growth—consistent with the recent growth slowdown. To keep our model as close as possible to DICE in the baseline, we calibrate the path of α_t to exactly reproduce economic growth in DICE when the DICE population is read into the model (see Fig. S1), though we consider much less optimistic growth paths in Fig. 3 by increasing β.

The second major modification of DICE is to include dependency ratio effects. As in most models of long-run macroeconomic activity, DICE assumes that the labor force scales linearly with population. Because of this, the distinction between workers and people is unnecessary and omitted from DICE for simplicity. We decouple the total population from the work force based on the age structure of our respective population scenarios (Supplementary Materials B). We denote L as the working-age population and N as the total population. Accordingly, the working-age population ratio is $\frac{L}{N}$ and the dependency ratio is $1 - \frac{L}{N}$. Note that modifying the labor input in this way implies an immediate and permanent decrease in L relative to DICE, where every person is assumed to be in the labor force. To avoid mechanically reducing total production from this redefinition, we add a constant scalar on labor productivity to replicate initial year output.

An additional minor modification is to scale emissions from land use change, E_{land}, with population. Emissions from deforestation and other land use change are exogenous

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[1] Formally, Bloom et al. can identify β for a given λ (i.e, the authors estimate the ratio of λ to β). Bloom et al take $\lambda = 1$ as a reasonable base case and, as noted above, what matters for the long-run effect of population on A is indeed the ratio (41; 10). Our use of $\lambda = 1$ as a base case is not an important assumption as long as the corresponding β is appropriately chosen.

and fixed in DICE. We endogenize this source of emissions such that they scale with N. In model specification m in time t,

$$E_{land,m,t} = \frac{N_{m,t}}{N_{DICE,t}} \times E_{land,DICE,t}. \tag{5}$$

If the population is $x\%$ larger in time t than in DICE, land-use emissions will be $x\%$ larger than in DICE. Industrial emissions are already specified within the original DICE structure to increase in population via the larger consumer and producer base. Thus, the model produces annual population-emissions elasticities near one, consistent with O'Neill et al. (30).

Fig. S1 demonstrates that the modifications we make to DICE are intended to exactly replicate DICE's output under the DICE population structure. Here we use the output from DICE2016R's BAU case posted on William Nordhaus' website and compare it to our modified version of the model under the same population structure and policy assumptions. Of course, when we change the population and policy assumptions these outputs change—the point here is to make explicit that the model is designed to stay as close to DICE as possible while endogenizing the key implications of population.

In summary, the modifications to DICE are as follows: (i) Technological progress increases in population size according to leading theories of economic growth; (ii) the distinction between total population and labor is explicitly represented, such that an economy with more children or retirees has lower GDP per capita, other things equal; and (iii) emissions from deforestation and other sources of land use change scale with population. Alternative model specifications in Fig. 3 (detailed in Supplementary Materials A) additionally modify the climate damages in DICE, replace DICE's climate module with Finite Amplitude Impulse Response (FAIR) climate module in line with recommendations from the National Academies (24), and increase the emissions impact of population.

To study the climate costs of population paths, a stance must be taken on a climate policy path. Advances in renewables technology and the implementation of (some) mitigation-inducing policy has rendered the DICE "business as usual" emissions path pessimistic relative to updated estimates of the world's likely emissions and warming trajectory (18). In our baseline case, we assume a path of mitigation rates calibrated to global emissions in 2030 and 2100 under the current policy trajectory estimate in Ou et al. (18). This assumed "current policy" trajectory exhibits substantial reductions of (net) emissions by the end of this century, but too slowly to meet international climate goals (Fig. 2a). We also consider a "low ambition" policy environment, which yields end-of-century warming similar to RCP 8.5 (Fig. 2b).

The comparative analyses between *Depopulation* and *Stabilization* hold policy—i.e., mitigation rates in each period—fixed and let the level of emissions differ based on the level of economic activity (which is in turn influenced by population size). In Fig. 3 we also consider an alternative climate policy path that is much more ambitious than the baseline. (See also Supplementary Materials A.)

Depopulation and Stabilization population paths

DICE takes a global population path as an exogenous input. A population path for our purposes specifies, for each five-year step, the total count of people in three age-intervals: working age, younger than working age, and older than working age. The data and replication materials to this paper include a fully interactive worksheet with data that constructs our *Stabilization* and *Depopulation* paths from UN World Population Prospects.[2]

The *Depopulation* path is the UN Medium projection until 2100, when that projection ends (14). We mechanically project further (negative) population growth, guided by (17)

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[2] `https://github.com/kevinkuruc/SemiEndogenous_DICE/blob/main/data/Population_Paths_Worksheet.xlsx`

and (42), the latter of which is a companion paper detailing the long-term decline scenario studied here. The growth rate falls by the same approximate rate of change as in the UN Medium projection for “Lower-middle-income countries” in 2100. Eventually, the global fertility rate converges to 1.66, the current TFR in the United States and, if anything, on the higher end of developed economies as a whole. The age composition of the population converges to $\{0.16$ younger, 0.46 working, and 0.38 older$\}$.

The *Stabilization* path is made by combining two UN projections: the Instant Replacement variant for High-income and Upper-middle-income countries, according to World Bank income groups, and the Medium variant for Lower-middle-income, Low-income, and No-income-group-available countries (so these latter three country groups have the same path to 2100 in *Stabilization* and *Depopulation*). After 2100, population growth stabilizes: Growth rates converge towards zero by 10% in every five-year step, and total population size reaches about 13 billion in the 23rd century. The age pyramid stabilizes with about half the population working in later centuries, which is approximately what the UN projects for 2100 for High-income countries.

We intend these paths, which we input to our version of DICE, not as detailed predictions. Instead, they are meant to be broadly representative of two contrasting abstract scenarios for the demographic future. For example, although we interpret 20-64-year-olds in UN projections as “working age,” our results are consistent with possible future changes in the age-profile of education and labor force participation, so long as these are approximately consistent with the difference between our two population scenarios (37). It could the be the case that “working ages” will shift to older ages, as people spend longer in education and also retire later. We need not specify, for illustration, exactly *why* 52% of the 2180 *Stabilization* population works while 48% of the *Depopulation* population does, so long as this is a plausible representation of differences in the aggregate stock of workers and consumers between the two population paths, however these might evolve.

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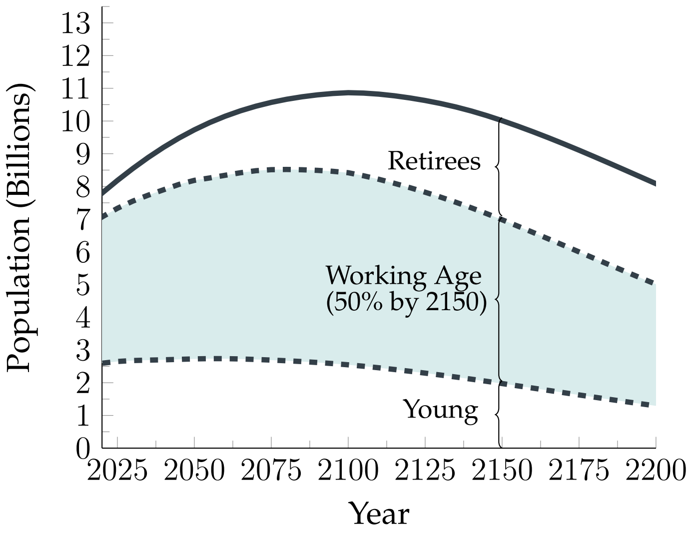
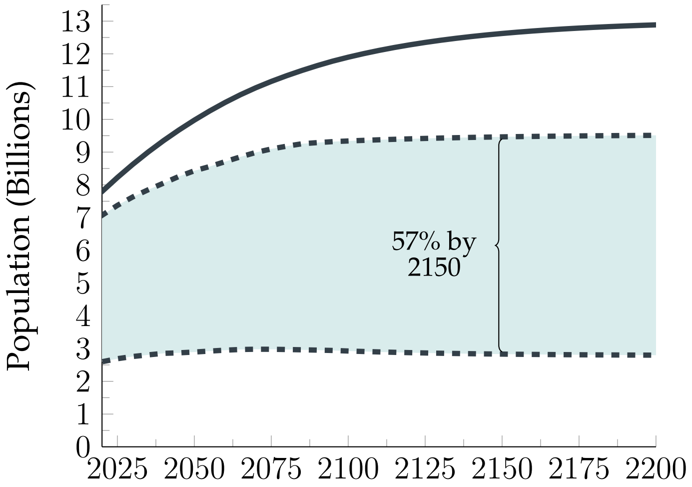
Figure 1: Two Population Paths: *Depopulation* and *Stabilization*

(a) *Depopulation* (from UN Medium projection and consistent with demographic consensus)



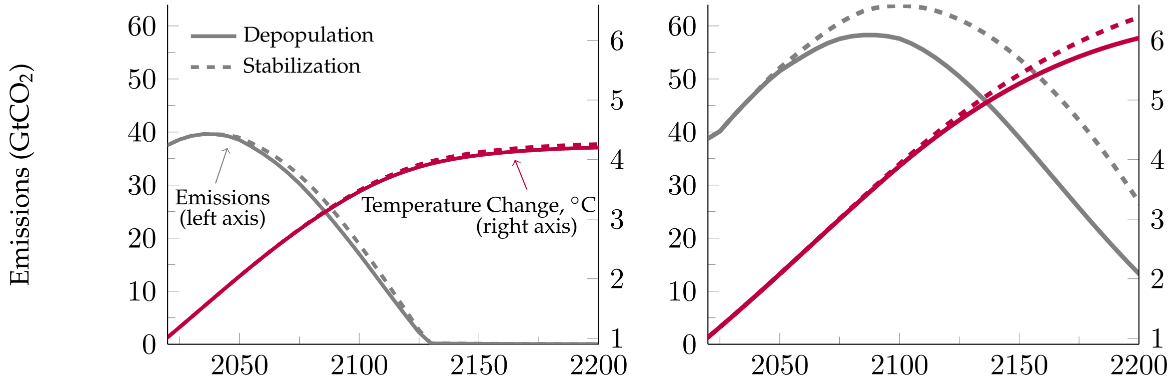
(b) *Stabilization* (from UN Medium and Instant-Replacement projections)



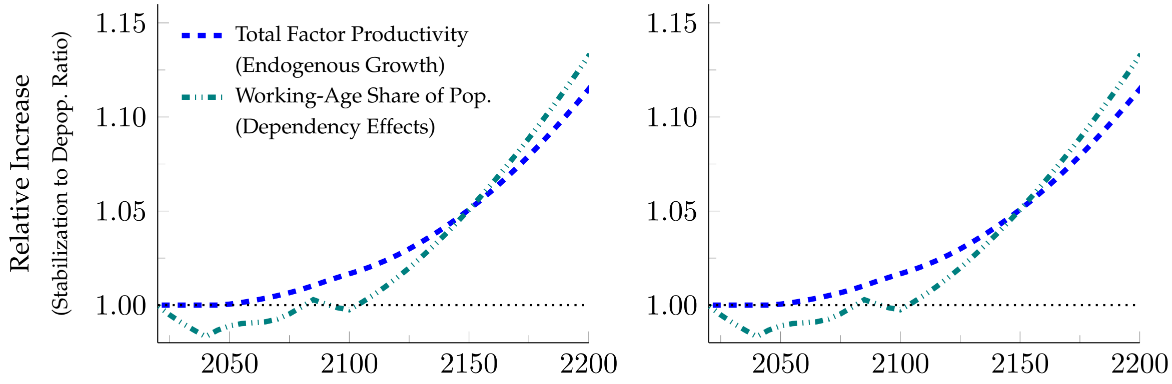
Notes: *Depopulation* and *Stabilization* population paths (inputs to the evaluation in Figs. 2 and 3) are derived from United Nations (UN) World Population Prospects 2019 projections. UN projections are available until 2100. *Depopulation* follows UN Medium. *Stabilization* combines Medium for Low-income and Lower-middle-income countries and Instant Replacement for High-income and Upper-middle-income countries. Population projections after 2100 are extended to match demographic facts for low-fertility populations (14; 17). See Methods.

Figure 2: Net of climate harms, average living standards are higher under *Stabilization* than *Depopulation*

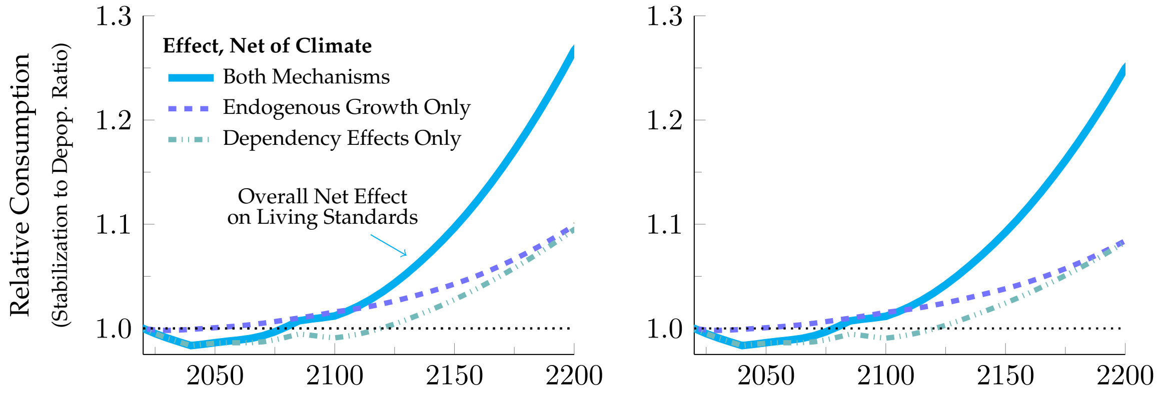
(a) Emissions and Temperature (Current Policy) (b) Emissions and Temperature (Low Ambition)



(c) Economic Benefits (Current Policy) (d) Economic Benefits (Low Ambition)

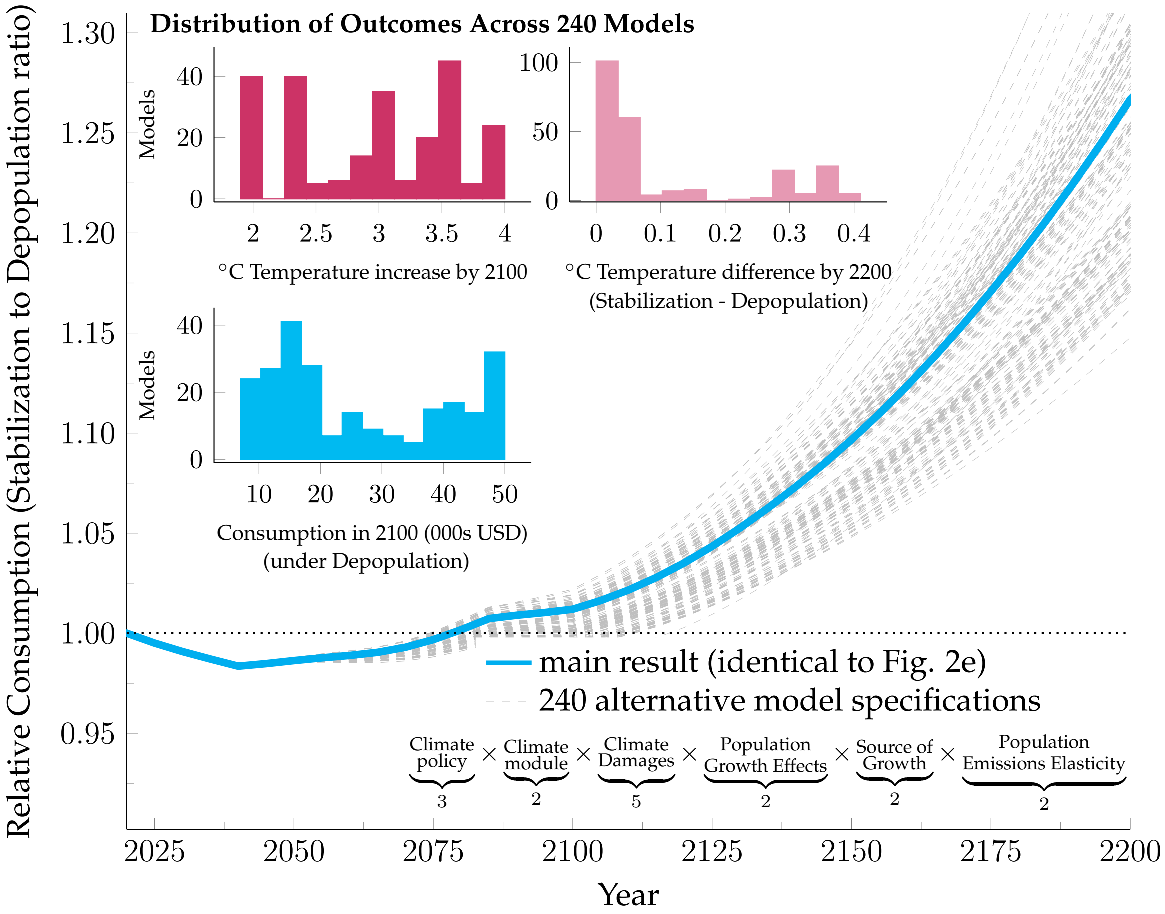


(e) Living Standards (Current Policy) (f) Living Standards (Low Ambition)



Notes: Left column depicts computations under a "current policy" scenario (18); right column assumes "low ambition" for future climate action (see Methods). Mitigation rates are common for both population paths within each column. (Top row) Emissions (left-axis) and temperature above pre-industrial (right axis) are shown in each population path and for each climate policy scenario. (Middle row) Increases in total factor productivity and working-age share under *Stabilization* relative to *Depopulation* are plotted as ratios. (Bottom row) Increases in average living standards (measured on scale of per capita consumption) between *Stabilization* relative to *Depopulation* are plotted as ratios for three versions of the model: (1) the full model with innovation benefits for endogenous growth, the demographic structure for dependency effects, and population-emissions harms (solid); (2) innovation benefits and population-emissions harms, with no demographic dependency effects (dash); and (3) demographic dependency effects and population-emissions harms, with no innovation benefits of endogenous growth (dash-dot). Results hold under a wide range of variations on baseline assumptions (Fig. 3).

Figure 3: Net economic benefits of *Stabilization* are robust across 240 alternative sets of assumptions and model specifications, even though models vary widely



Notes: Alternative specifications are generated by crossing each of the six model dimensions indicated: climate policy (3 variants); climate modules (2 variants); climate damages (5 variants); amount of TFP growth (2 variants); source of TFP growth (2 variants); and emissions intensity of population (2 variants). See Section A for details on each variant. The three inset histograms plot, for these 240 model specifications, the distributions of: year-2100 temperature change from pre-industrial under the *Depopulation* scenario (left); year-2200 temperature *difference* between *Stabilization* and *Depopulation* (right); and year-2100 consumption per capita under the *Depopulation* scenario (bottom). The histograms illustrate that these 240 alternative models are substantially different, despite their convergent finding that net living standards are higher under *Stabilization* compared to *Depopulation*.

Supplementary Materials: A Larger World Population Raises Average Living Standards, Net of Climate Damages

A 240+ alternative model specifications

In Fig. 3, the model is modified along six dimensions: climate policy (3 variants); climate modules (2 variants); climate damages (5 variants); amount of TFP growth (2 variants); source of TFP growth (2 variants); and emissions intensity of population (2 variants). Each variation is detailed below. We cross all combinations for a total of 240 model specifications.

$$\underbrace{\begin{matrix}\text{Climate}\\ \text{Policy}\end{matrix}}_{3} \times \underbrace{\begin{matrix}\text{Climate}\\ \text{Representation}\end{matrix}}_{2} \times \underbrace{\begin{matrix}\text{Climate}\\ \text{Damages}\end{matrix}}_{5} \times \underbrace{\begin{matrix}\text{Population} \rightarrow \text{TFP}\\ \text{Pass Through}\end{matrix}}_{2} \times \underbrace{\begin{matrix}\text{Source of}\\ \text{TFP Growth}\end{matrix}}_{2} \times \underbrace{\begin{matrix}\text{Population}\\ \text{Emissions Elasticity}\end{matrix}}_{2} = 240$$

For example, one of these 240 combinations has: ambitious climate policy, the FAIR climate module, DICE climate damages, slower TFP growth, TFP growth arising from population, and a population emissions intensity that is higher than in DICE. We detail each possibility below.

Climate Policy. We consider three climate policy scenarios: Current Policy, No Policy, and Ambitious Policy. The Current Policy scenario is calibrated to 2030 and 2100 global emissions estimates from Ou et al. (18). No Policy is a scenario meant to approximate a worst-case scenario resulting in similar end-of-century warming as under RCP 8.5. Ambitious Policy sets net industrial emissions to zero immediately. The two alternatives here are constructed not to necessarily be realistic but rather to demonstrate that the main results hold over a wide range of socio-economic-political environments.

Climate Representation. DICE's climate representation was originally designed to integrate simply within a macroeconomic model. Since its design, there have been numerous attempts to produce more realistic, but still tractable, climate representations for the purposes of integrated assessment models. The Finite Amplitude Impulse Response (FAIR) is one such model that has been recently recommended in a National Academies' report on better practices in integrated assessment modeling (24).

The climate representation is separable from the economic modules of DICE, so it is straightforward to independently modify this piece of the model. We use an implementation of FAIR that was coded into the Julia programming language, where the rest of our model is run. Details are available at: `https://github.com/anthofflab/MimiFAIR`.

`jl`.

Because FAIR may be of special interest, we additionally replicate Fig. 2 below using the FAIR climate representation (with other model components set to baseline). FAIR implies *less* warming for a fixed set of emissions, and our core results are robust to this modification.

Climate Damages. We consider five alternative specifications for damage functions. First, we use the standard specification for damages in DICE2016:

$$D_t = \theta_1 T_t + \theta_2 T_t^2$$
$$Y_t^N = (1 - D_t) Y_t^G.$$

Here D is the fraction of output lost to climate damages, T is the temperature (Celsius, above pre-industrial), Y^N is net-of-damages output that can be consumed and invested.

A modification that allows for the economic effects of tipping points is straightforward due to recent work by Dietz et al. (27). Dietz et al. presents a reduced-form, additive modification of standard quadratic damage functions with coefficients ξ_1, ξ_2:

$$D_t = (\theta_1 + \xi_1) T_t + (\theta_2 + \xi_2) T_t^2. \tag{6}$$

We use exactly the coefficients reported in Fig. 5 of Dietz et al. (27).

A second alternative considers much larger damages than DICE, estimated in an influential paper by Burke et al. (26). The damage estimates constructed there come from a non-linear model disaggregated to the country level. DICE is specified at a coarser level of aggregation, so we implement the reduced-form version presented in Fig. 5d of Burke et al., linking global temperatures to global losses of GDP.[3]

A third alternative considers the possibility that temperature also influences economic growth rates, as considered by Moore and Diaz (28). In Moore and Diaz, the model is disaggregated to multiple regions making exact replication infeasible. We instead implement their functional form at the global level and employ coefficients on the higher end of their proposed range in an effort to be conservative (against our findings). Specifically, the rate of TFP growth becomes:

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[3] We translate the graphical depiction to numerical values using data extraction software. We then estimate a cubic function, $D = \alpha_1 T + \alpha_2 T^2 + \alpha_3 T^3$ for the corresponding damage function.

$$g_{A,t} = \alpha_t L_t A_t^{-\beta} - \varepsilon \tilde{T}. \tag{7}$$

We calibrate ε such that a 1-degree increase in $\tilde{T}$ reduces GDP growth by 1 percentage point per year, consistent with the largest negative impacts on GDP growth presented by Moore and Diaz. Also following their implementation, we use what they call "effective temperature," $\tilde{T}$, to allow for adaptation. The idea is to subtract a function of past temperatures such that the long-run effect of a fixed level of warming tends back to zero. We numerically implement this in a slightly different way than Diaz and Moore owing to differences in model construction, but we retain that warming (i) passes through to $\tilde{T}$ one-to-one in the immediate-term and (ii) has a near-zero effect on growth rates after 30 years at that level.[4]

The fourth and final alternative damage function comes from Dietz and Stern (2015), who assume temperature can damage the path of TFP directly (29). Specifically,

$$A_{t+1} = (1 - D_t^A) \frac{A_t}{1 - g_{A,t}}. \tag{8}$$

Dietz and Stern split total damages between TFP and GDP damages. To be conservative in our implementation (in the sense of maximizing effective damages, which is against our findings), we apply full DICE-level damages to *both* TFP and GDP (i.e., $D_t^A = D_t$).

All of these damage function modifications substantially increase the economic costs of global warming under both population paths. Because the differences in temperature are small across the two population paths (0.06° C in the baseline run comparing *Stabilization* to *Depopulation*; see Fig. 2a), large damages per degree do not translate into large damage differences across the scenarios. Even in model specifications using the most extreme damage functions, temperature differences are small and the net benefits of *Stabilization* relative to *Depopulation* remain.

Population Emissions Intensity. To avoid the possibility of understating the population effects of emissions, we mechanically increase the emissions elasticity of population to exactly one in each period. In DICE, industrial emissions ($E_{Ind,t}$) come from economic production, not people.

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[4] Specifically, Moore and Diaz define $\tilde{T}_t = \sum_{j=1850}^{j=t} (T_j - T_{j-1}) e^{-a(t-j)}$ such that if warming is fixed at some level in the long-run $\tilde{T} \to 0$. For simplicity, and because our version of DICE does not track temperatures back to 1850, we instead subtract a rolling average of the prior 30 years. This is chosen to match Moore and Diaz's calibration where the effective temperature from a one-time temperature shock is near-zero after 30 years.

$$E_{Ind,t} = \underbrace{(1 - M_t)}_{\substack{\text{Mitigation}\\ \text{Rate}}} \times \underbrace{\sigma_t}_{\substack{\text{Emissions-}\\ \text{Intensity}}} \times \underbrace{Y_t}_{\text{GDP}}$$

Further, consistent with medium- to long-run macroeconomic models, all working-age people work and all available capital is employed in each model period. Therefore, an additional child today, who does not contribute to GDP, does not immediately increase emissions in the model. Emissions increase once the child ages into the workforce. Put differently, the model assumes that productive capacity is met with or without the child (e.g., a new child does not cause the unemployment rate to fall), so that the child's consumption must be substituting for some economic activity that would have otherwise taken place.

We relax this standard assumption to show that it is not crucial to our results. In particular, beyond scaling land-use emissions to population as we do in every model interaction, we redefine industrial emissions as

$$E_{Ind,t} = (1 - M_t) \times \sigma_t^N \times N_t, \tag{9}$$

where N_t is the total population size. This functional form makes it necessarily true that if in period t *Stabilization* has a population 10% larger than *Depopulation*, emissions will also be 10% larger. We calibrate σ^N to again replicate DICE2016's baseline implementation to avoid redefinitions that change baseline outcomes; we fit the equation $\sigma_t^N \times N_{t,DICE} = \sigma_t \times Y_{t,DICE}$.

Population → TFP Pass-Through. In the baseline model we calibrate β in $g_{A,t} = \alpha_t L_t^{\lambda} A_t^{-\beta}$ to reflect leading empirical estimates (13). We calibrate α_t to replicate DICE's TFP path.

DICE has an optimistic view of future TFP growth, which in our setting implies a high pass-through from population to TFP. To ensure that this optimistic calibration does not drive the main results, we make ideas "harder to find" by increasing β. Specifically, we increase our baseline β from 3.1 to 4.0. To put this in perspective, TFP grows by 3.5-times by 2200 with $\beta = 3.1$, but only 1.5-times with $\beta = 4$, a substantial reduction. This modification contributes to the lower end of the end-of-century consumption distribution in Fig. 3. However, the *relative* benefit of population remains: *Stabilization* continues to find more of these scarcer improvements in living standards.

Source of TFP Growth. The preceding discussion makes clear that merely adjusting the productivity of labor in producing ideas does not make much difference to the main results. But what if the structure of endogenous growth were modified to de-emphasize people? For example, Dietz and Stern (2015) implement the Romer (1986) endogenous growth model where economic capital is the key variable (29; 43). We implement the possibility that endogenous growth depends on total output—not on people, *per se*. To do so, we assume that some fraction of all available economic resources, Y_t^G, are devoted to idea production.

$$g_{A,t} = \alpha_t^Y Y_t^G A_t^{-\beta}. \tag{10}$$

Equation 10 recognizes that people need research labs, computers, and other productive economic capital to produce knowledge. Other things equal, a larger economy—meaning here the combination of people and other economic resources—can generate more new knowledge.

This modification ends up mattering very little to the main results for two reasons. First, people are a primary input to Y^G, so *Stabilization* also has more Y^G. Second, capital in the economy is produced by people. Even in a specification where capital was the *only* input to idea-creation, large populations support larger capital stocks, which then support more knowledge generation. A key insight of the literature inspired by Romer (9) is that a large global population implies a large global economy which implies more total knowledge creation (which then makes everyone better off because ideas are non-rival and can be shared by everyone).

B Human capital

Both Nordhaus' DICE model and the Romer-Jones models of endogenous growth abstract away from human capital to focus on their core mechanisms. Human capital is economists' term for the resources that exist within people (skills, knowledge, experience, physical health, etc.) that affect each person's productive capacity. During the rapid population growth of the 20th century, levels of human capital (often measured in terms of educational attainment and similar proxies) have risen considerably. They are expected to continue to rise (31). In this section, we augment the baseline Nordhaus and Romer-Jones models to embed insights from a literature focused on the relationship between population change and human capital. We also draw upon Doepke, et al. (33) to review other theories and evidence about human capital as these pertain to our methods and results.

Marois, Gietel-Basten, and Lutz (22) have recently proposed (with the example of

China) that the effect of reduced fertility on the dependency ratio might be mitigated, for the coming decades, by increases in human capital (both education and early-life health) and by changes in working lifespan, such that older adults are more likely to participate in the labor force. They propose a productivity-weighted labor force dependency ratio to represent these changes in a reduced form way. The focus in Marois et al. is different from ours. Whereas Marois et al. compares the present (with its levels of human capital) to a future (with increased human capital), our work compares two alternate futures.

Nonetheless, to assess whether accounting for productivity-weighted labor would upset any of our conclusions, we incorporate the Marois et al. idea into our comparison of population paths. To do so, we multiply the labor force L in each period (in both scenarios) by the ratio of two quantities that Marios, *et al*. provide in their SI Table 4: the size of the productivity-weighted labor force and the size of the unweighted labor force.[5] We mechanically extend their projections beyond where they stop in 2070, capping this ratio at 2. We are agnostic about how exactly to interpret this reduced-form adjustment: it could represent any combination of human capital and labor-force participation changes.

Appendix Fig. S3 shows that our main qualitative result is robust to this change. This is because increases in the human capital of the workforce will make workers more valuable under both *Stabilization* and *Depopulation*. Despite a different focus, our findings of relative net harms of depopulation are consistent with the findings of Marois et al. Indeed, our core finding is that a forgone worker (lost to a declining population) represents a large opportunity cost to the economy. Therefore, the opportunity cost is only larger in a Marois et al.-like future in which that forgone worker would have had more human capital.

A further possibility is that population *Stabilization*, rather than *Depopulation*, would have an *endogenous effect* on future investments in human capital, lowering such investments. For example, Gary Becker's classic quality-quantity economic model of fertility is built upon the idea that a family choosing to have more children depletes a budget that could otherwise be used to invest in human capital.

As an empirical matter, several pieces of evidence suggest that such human capital dilution effects of a larger population would not be so strong as to overwhelm the productive expansion arising from population growth.

First, the quantity-quality tradeoff is less relevant today than in the past. As Doepke, et al. (33) explain in their review of the empirical literature on fertility decision and

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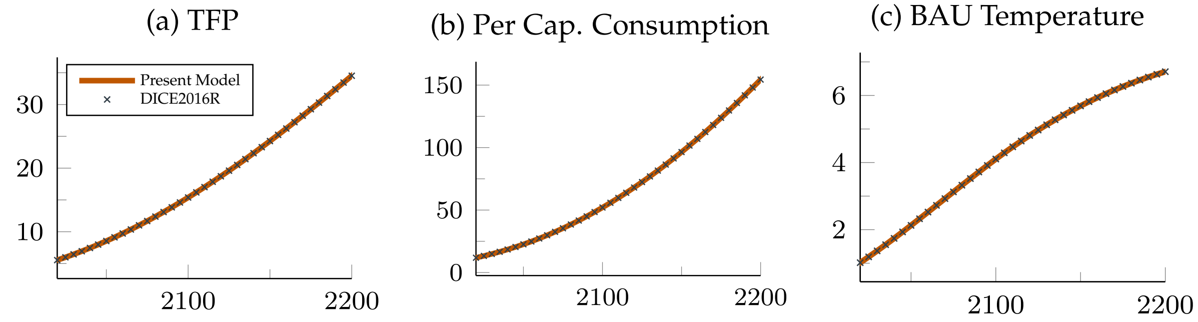
[5] In doing so, we implicitly assume that these *ratio* changes for China can plausibly reflect ratio changes for the world as a whole, although some populations have more human capital and some populations have less.

child investments: "The tradeoffs emphasized by these models still exist and continue to be important in explaining fertility behavior in many places, including lower-income countries. What has changed, however, is that these [quantity-quality] tradeoffs no longer drive the major variation in the data for high-income countries" (p. 2). This is true for a number of reasons. For example, many of the private, family-level investments in early-life health that were important historically are no longer important sources of variation in populations where, for example, mothers no longer face starvation risk, sanitation infrastructure is present, and childhood vaccines are standard. These factors are no longer strongly correlated at the household or family level with wealth or fertility. In the specific context of our study, it is important to understand that our counterfactual *Stabilization* path in large part considers *arresting* the projected future decline in fertility, rather than dramatically increasing fertility rates relative to today. So there should be little reason to assume human capital investment would decline relative to today.

Second, and more importantly, the only foreseeable, plausible path to encouraging higher fertility rates would be one that changes the implicit (and explicit) "price" of raising children—for example, through large-scale public investment in income support for parents; free, universal, and flexible childcare; and improved education, healthcare, and other direct, public investments in children. Such an environment would have fundamentally different implications for human capital accumulation, compared to either the Malthusian model (the evidence for which arises from exogenous population shocks, rather than such "price" changes) or the quantity-quality model (the evidence for which typically arises from exogenous family size or income shocks, rather than such "price" changes). In short, a policy that lowered the cost to parents of human capital investment in children could increase both the quality and quantity of children.

Perhaps the most persuasive evidence against the possibility that population growth would strongly reduce human capital in the modern world is recent historical experience: The explosive population growth of the past century has coincided with the most extensive growth in human capital in history. (See, e.g., Fig. S6.) Indeed, in endogenous growth theory, Galor and Weil (5) characterize the post-Demographic Transition world as one in which moderate population growth exists alongside vast improvements in human capital and productivity.

Figure S1: Modified model with DICE population reproduces DICE's output


(a) TFP

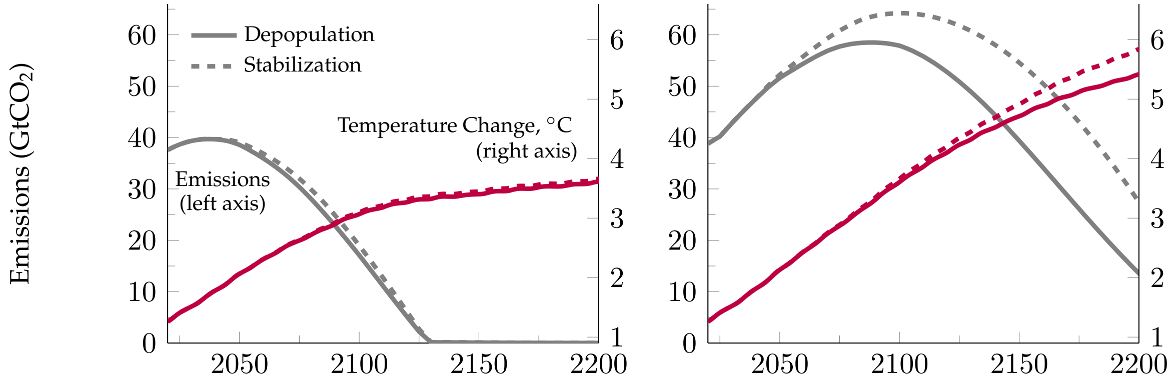
(b) Per Cap. Consumption

(c) BAU Temperature

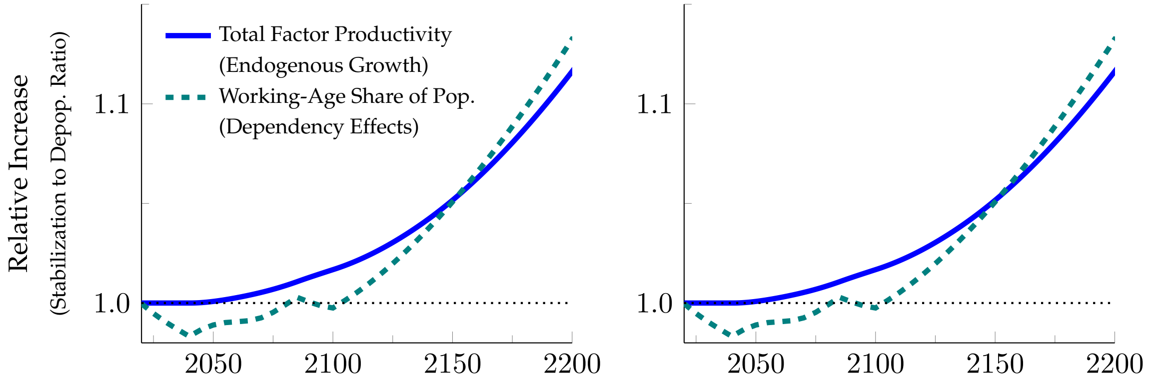
Notes: Verification that the modified version of DICE—with endogenized TFP and land-use emissions—exactly replicates DICE2016R when the original DICE population and policy trajectory is assumed. The output from DICE2016R is available at `https://williamnordhaus.com/dicerice-models`.

Figure S2: Replication of Fig. 2 using FAIR climate module

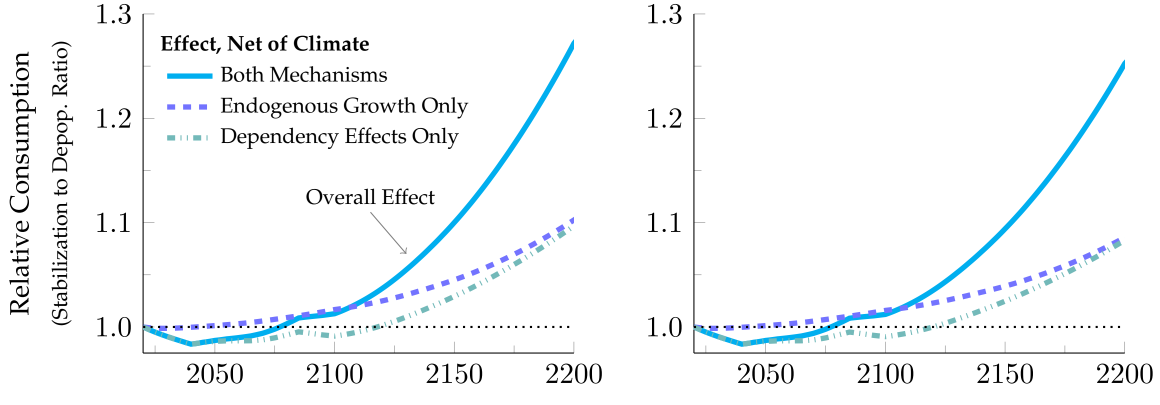
(a) Emissions and Temperature (Current Policy) (b) Emissions and Temperature (Low Ambition)



(c) Economic Benefits (Current Policy) (d) Economic Benefits (Low Ambition)

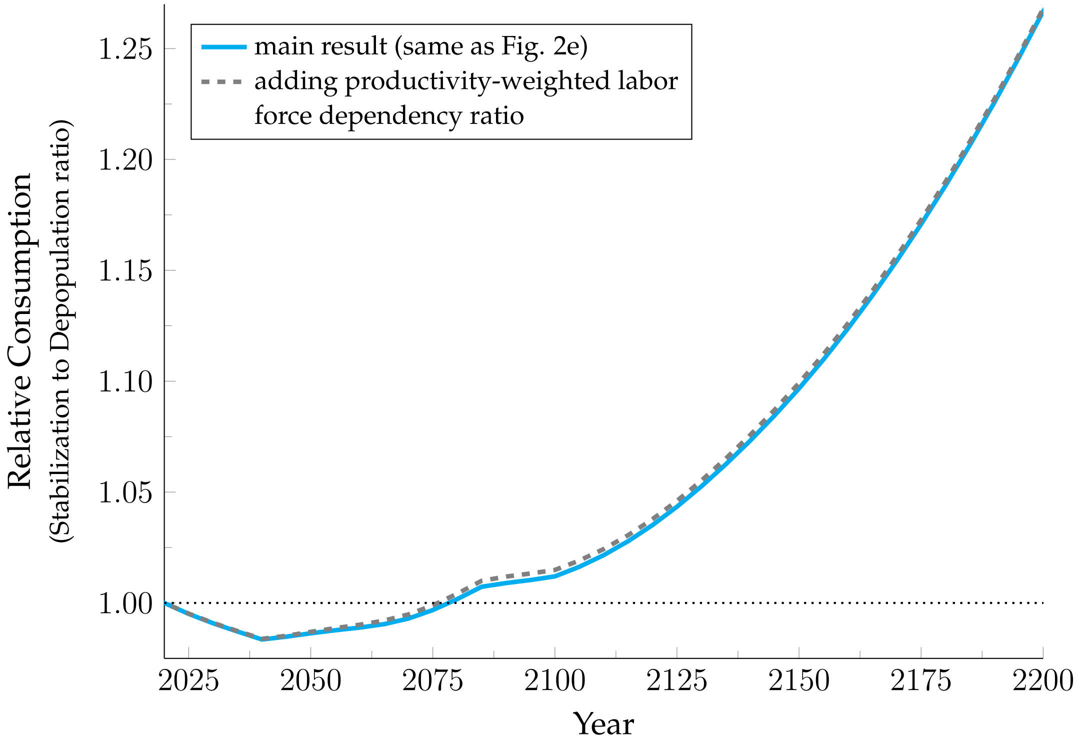


(f) Living Standards (Current Policy) (f) Living Standards (Low Ambition)



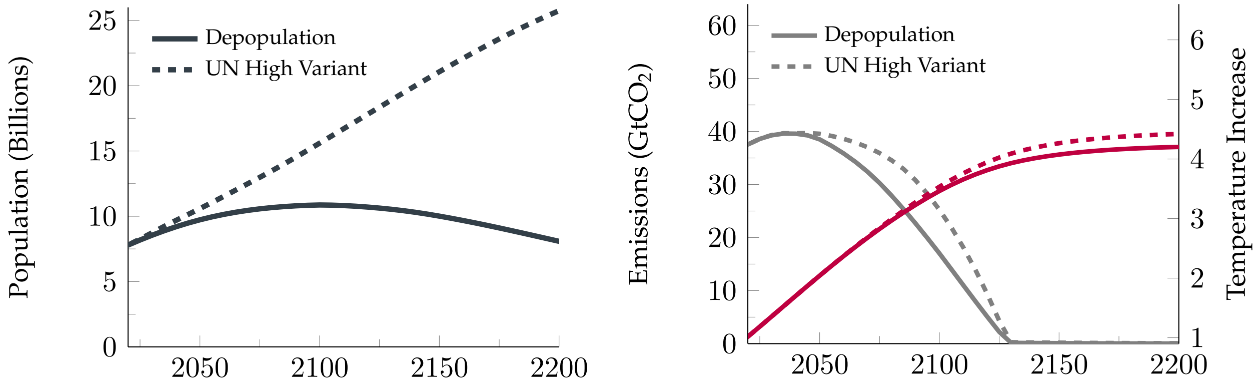
Notes: A replication of Fig. 2 in which the climate representation has been replaced by the FAIR model.

Figure S3: Main result is robust to adjusting labor supply to account for future changes in human capital

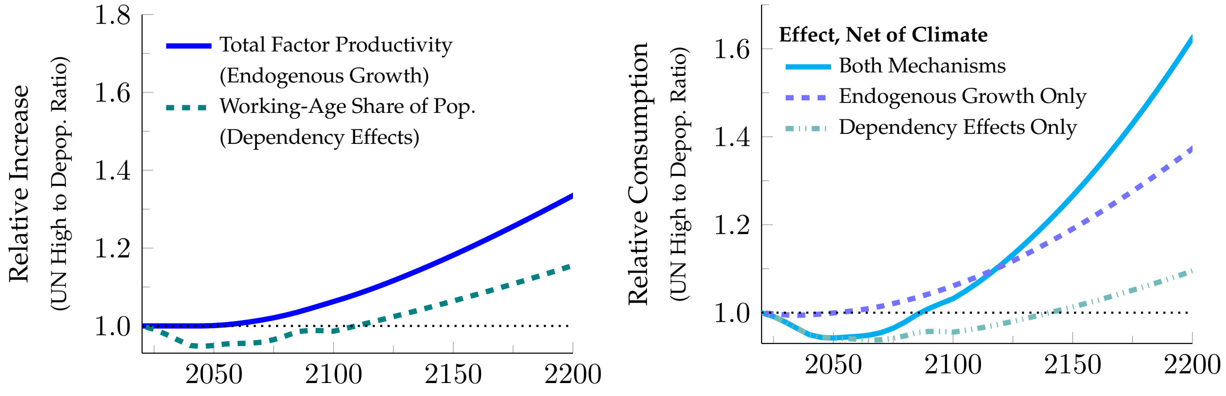


Notes: A replication of the overall effect in Fig. 2e in which labor supply is scaled by human capital adjustments, according to the productivity-weighted labor force approach of Marois, Gietel-Basten, and Lutz (22) (see Supplementary Materials B). This approach accounts for a future in which workers are better educated, work longer careers, or are otherwise more productive, on average.

Figure S4: Benefits of population remain large when comparing UN High population projection with *Depopulation*


(a) Population Differences

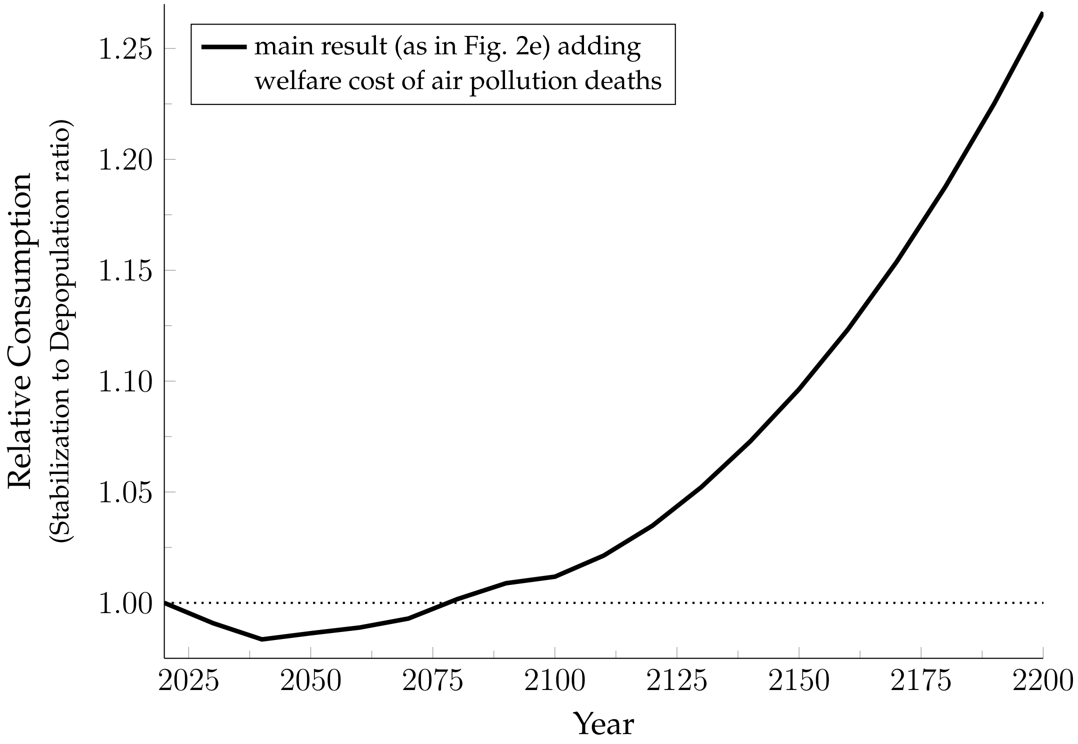
(b) Emissions and Temperature


(c) Economic Benefits

(d) Living Standards

Notes: A replication of Fig. 2 where an extension of the UN High variant, rather than *Stabilization*, is compared with *Depopulation*. Uses “current policy” mitigation pathways in both population scenarios.

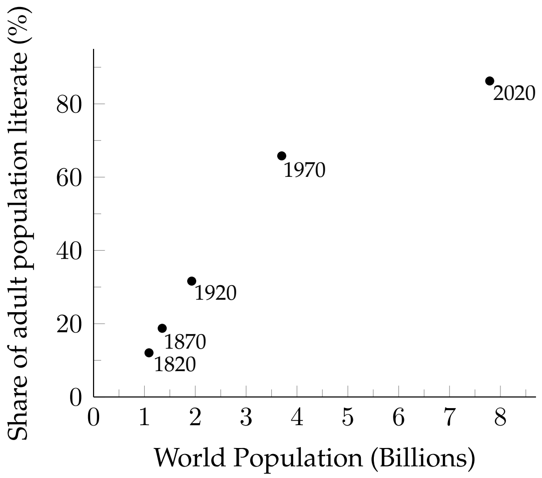
Figure S5: Main result is robust to adding mortality costs from air pollution



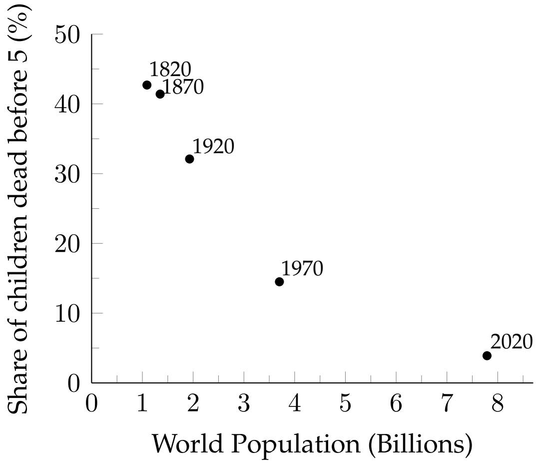
Notes: A replication of the overall effect in Fig. 2e in a model modified to include the welfare costs of air pollution. Air pollution harms are estimated using model output from (44)—a similar macroeconomic climate model that accounts for the co-harm of air pollution from industrial emissions. Following their approach, each percentage point of increase in mortality is worth two percentage points of consumption (so that the value of a life year is worth two years of consumption, consistent with results from the literature estimating the value of a statistical life). The additional per capita mortality from air pollution is small because the emissions differences between the two population paths are small due to population momentum (see Fig. 2a).

Figure S6: Human development has progressed as the world population has grown

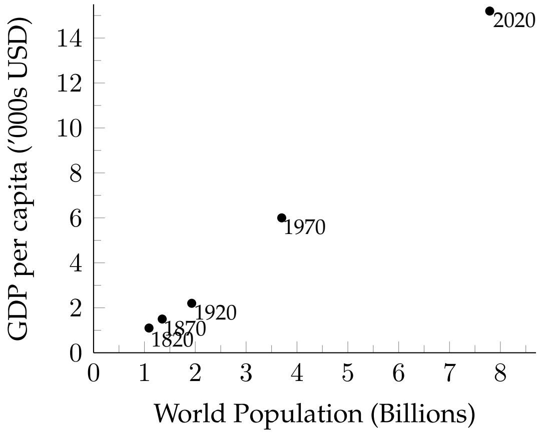
(a) Literacy (World)



(b) Child Mortality (World)



(c) Living Standards (World)



Notes: Plot of Our World in Data series available at `https://ourworldindata.org/` in 50-year intervals (or nearest available prior year).